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Sensitive variables for applying biochar as a fertiliser substitute and a method to sequester carbon in soils: a wheat crop scenario.

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Abstract

This research reviews the displacement of phosphorus fertilisers in wheat cropping regions using biochar (biologically derived charcoal). The research aim was to assist agriculturalists to navigate soil carbon mitigation incentives using iterative planning processes, enabling a balanced approach between soil biochar sequestration, conventional productivity co-benefits, and attitudes to risk. This research quantifies conventional productivity benefits from the adoption of carbon soil sequestration, and the value of carbon sequestered, with scenarios for various prices for biochar, single superphosphate, and carbon. The biochar sequestration modelling results indicate that a reduction of phosphorus fertiliser use in cropping regions was possible when applying large quantities of biochar to the soil. The cost-effectiveness of using biochar in cropping systems was found to be insensitive to phosphorus fertiliser price or carbon market values. In contrast, the commercial viability of using biochar in cropping systems was highly dependent on the price of biochar.

Introduction

In the long-term, a sustainable management strategy that maintains or increases carbon stocks, while producing an annual sustained yield of timber, fibre, food, or energy will generate the largest on-going mitigation benefit for agricultural lands [1]. Agricultural and forestry products may also provide a significant percentage of inputs required for electricity, steel, concrete, synthetic cloth, liquid fuels (methanol, ethanol, butanol, biodiesel), solid fuels (logs, chips, briquettes, pellets, biochar), gaseous fuels (synthesis gas, biogas, hydrogen), or fertilisers [2-4]. Polygeneration systems provide multiple energy sources and biomass products, with some systems accepting multiple biomass input fuels [3]. The possibilities and technology options available for biomass conversion are enormous. This research analyses one option of using pyrolysed biomass as a soil conditioner in a low rainfall (less than 300 mm growing season rainfall) wheat region. This analysis was undertaken to quantify the market mitigation and market adaptation potential of using biomass-derived charcoal, known as biochar, as a soil

amendment to displace single superphosphate (0%N, 8.8%P, 0%K, 11%S) fertiliser applications in a 50 ha wheat cropping system scenario in the SW of WA.

Soil carbon sequestration markets in agricultural soils are a known potential synergy between climate change adaptation and mitigation, as it creates an economic commodity (the soil carbon) for agriculturalists, which also improves the productivity of the land, reduces soil erosion, and increases fertiliser use efficiency [4-8]. This analysis quantifies the conventional benefits from any gains in productivity associated with the adoption of carbon soil sequestration, and the value of carbon sequestered, with scenarios for various prices for biochar, single superphosphate, and carbon. The aim was to assist agriculturalists to navigate soil carbon mitigation incentives using iterative planning processes, enabling a balanced approach between soil biochar sequestration, conventional productivity co-benefits, and attitudes to risk.

Biochars range in complexity from graphite-like carbon to high molecular weight aromatic rings which are known to persist in soil for thousands of years [9]. Therefore, the conversion of biomass to biochar, and subsequent application to soil results in a relatively long-term carbon sink and store. Converting biomass to biochar in controlled conditions leads to around 50% of the initial carbon remaining in the biochar, which results in biochar of approximately 80% carbon content. This contrasts with the low amount of initial biomass remaining as biochar after burning (3%) [10]. The efficiency of conversion in terms of retaining biomass carbon in the biochar is highly dependent on the type of feedstock, although variation is reduced by pyrolysis temperatures within 350-500°C [10]. In terms of regional industry development, large pyrolysis units coupled with wide-scale biochar application to soil may address the dilemma of soil nutrient loss from large-scale bioenergy production. In addition to deep-banding, common methods of biochar application to soils are broadcasting, seeding application, topdressing, aerial delivery, specific application to ailing vegetation at the root, and also ecological delivery via animal excreta [11]. Biochar transport is also relatively efficient on a weight basis, as the biochar mass is 70–80% less than the original dry biomass [12].

Technical Model

The technical results are based on existing crop yield research data regarding biochar additions alongside fertiliser applications in the SW of WA. The data was used to determine the minimum equivalent price of biochar required to obtain the same wheat yield while reducing the annual single superphosphate (SSP) fertiliser application by half. The primary data were derived from research undertaken by Blackwell et al. (2007, 2008, 2010, pers. comm.), conducting biochar-fertiliser-crop interaction research for over six years. Note that large uncertainties remain on the

mechanisms of how biochar applications to soil impact surrounding ecology, and also the specific processes that the substance influences in particular crops in specific soil types, regions, and climates. However, as stated by Blackwell (2010), the effects of biochar addition in the soils in WA seem to be highly related to its influence of P use by wheat. Providing total P loadings equivalent to 100 kg ha⁻¹ of SSP (~9 kg of P ha⁻¹) requires around 160 kg of biochar ha⁻¹ [13]. Due to the medium-to-low nutrient content of most biochars, applications are more commonly considered soil conditioners rather than fertilisers [14]. In contrast to fertilisers that predominantly aim to increase nutrient inputs, soil conditioners tend to enhance plant growth by retaining existing nutrients, and improving soil physical and biological properties [10, 15].

	Site A	Site B	Site C
Characteristic			
Soil type	Sandy loam	Sandy loam	Low P sand
Growing season rainfall (mm)	288	204	210
Approx. full fert. rate yield (kg ha⁻¹)	750	2,150	1,800
Approx. ½ fert. rate yield (kg ha ⁻¹)	600	1,850	1,850
Approx. zero fert. yield (kg ha ⁻¹)	350	1,750	-
Approx. ½ fert. rate +BC yield (kg ha⁻¹)	800	2,200	2,300
Increase attributed to BC (kg ha ⁻¹)	227	320	430
Approx. percentage increase (%)	~28	~14	~18

Table 1: Three significant positive fertiliser and BC responses from low rainfall wheat crops in WA.^a Sources: [11, 16-18].

The model includes two applications of biochar over the 15 years, applied in year zero, and year eight. The model ignores all production inputs and outputs, and simply calculates the market adaptation and market mitigation potential difference between using an average “full rate” of SSP (90 kg ha⁻¹), and a “half rate” of SSP with deep banded biochar equivalent to 1 t ha⁻¹. The model assumes both applications will achieve an identical wheat yield. Therefore, a wheat price is not necessary for the model. The application cost of deep banding the biochar t⁻¹ ha⁻¹ year⁻¹ was modelled as AUD110. The half rate of SSP applied ha⁻¹ year⁻¹ was 45 kg, which is

^a Note that mono-ammonium phosphate, mineral fertilisers, and single superphosphate were used as fertilisers. Also some of the “half rates” were actually slightly more than half, and the author recommends going to the original sources for detailed information regarding the precise agronomic characteristics of the research.

approximately equivalent to an annual application 4 kg of P ha⁻¹. The annual application cost of the SSP was modelled as AUD20 ha⁻¹, GST inclusive. The application cost of the SSP was modelled as identical between the half and full rates, taking into account the significant site loading and servicing requirements involved. The biochar price (delivered to farm) was modelled at intervals of AUD50, between AUD0 and AUD450 t⁻¹. Similarly, the cost of SSP (delivered to the farm) was modelled at intervals of AUD50, between AUD250 and AUD1,250 t⁻¹. Carbon values were also included in some analyses, and were modelled at intervals of AUD5 tCO₂-e, between AUD0 and AUD100 tCO₂-e. A real discount rate of 8% was used, and the inflation rate was assumed to be 3% p.a. All capital and maintenance costs were based on average current prices and are GST inclusive unless stated (Table 3). On average, the recalcitrance of biochar can be approximated as 80% of the original mass over the first several decades, depending on the environmental exposure and the original biomass characteristics [19], and the model uses an 80% recalcitrance rate. Equation 1 shows the total sequestration (tCO₂-e ha⁻¹) for an example of one tonne of applied biochar for each ha over the 15 year interval.

$$1 \text{ tC ha}^{-1} \times 80\% \text{ recalcitrance} \times 3.666 \text{ tCO}_2\text{-e tC}^{-1} = 2.933 \text{ tCO}_2\text{-e ha}^{-1}$$

Equation 1: Total modelled sequestration (tCO₂-e ha⁻¹) over the 15 years.

No calculation for either embedded or operational emissions for either SSP or biochar application were included. Despite the importance of fertiliser as a direct and indirect source of carbon emissions [20], the analysis did not quantify in detail any change in project sequestration from fertiliser use reduction or additional mechanical use for biochar deep banding. The research deemed that the relatively small area modelled, and the energy use per tonne of SSP production and use was sufficiently small relative to changes in SOC derived from both the impact of tillage practices, sequestered biochar, and crop root mass turnover. Any impact of the biochar addition reducing soil methane emissions, as reported by Rondon et al. (2005), was not included in the mitigation calculations.

Adaptation and Mitigation Model Results

The summary of all NPC calculations for all combinations of biochar and fertiliser scenarios are shown in Table 2, and an example of one of the NPC calculations is shown in Table 3. The Tables show that the modelled half rate of SSP (45 kg ha⁻¹ year⁻¹) and biochar (BC) (1 t ha⁻¹ year⁻¹) were only cost competitive with the full rate of SSP (90 kg ha⁻¹ year⁻¹) when the BC purchase price was a very small percentage of the price of the SSP per tonne. The model assumed a zero carbon price for the approximate 5.866 tCO₂-e ha⁻¹ sequestered in the soil,

which was solely derived from the BC addition. Therefore, the market mitigation potential of the activity in this scenario is 2.933 tCO₂-e ha⁻¹.

SSP @ 90 kg ha ⁻¹		NPC of SSP @ 45 kg ha ⁻¹ & BC @ 1 t ha ⁻¹ h (BC AUD t ⁻¹)						
SSP AUD t ⁻¹	SSP NPC		0	50	100	150	200	250
250	414		-	-	-	-	-	-
300	459		-	-	-	-	-	-
350	505		514	-	-	-	-	-
400	551		537	-	-	-	-	-
450	597		560	645	-	-	-	-
500	642		583	668	-	-	-	-
550	688		606	691	-	-	-	-
600	734		629	714	798	-	-	-
650	780		652	736	821	-	-	-
700	826		675	759	844	-	-	-
750	871		698	782	867	952	-	-
800	917		720	805	890	975	-	-
850	963		743	828	913	997	-	-
900	1,009		766	851	936	1,020	-	-
950	1,054		789	874	958	1,043	1,128	-
1,000	1,100		812	897	981	1,066	1,151	-
1,050	1,146		835	919	1,004	1,089	1,174	-
1,100	1,192		858	942	1,027	1,112	1,197	-
1,150	1,237		881	965	1,050	1,135	1,219	1,304
1,200	1,283		903	988	1,073	1,158	1,242	1,327
1,250	1,329		926	1,011	1,096	1,180	1,265	1,350

Table 2: The NPC results over 15 years for both the baseline scenario of full single superphosphate (SSP) application rate (90 kg ha⁻¹ year⁻¹), shown in the second column, and the half rate SSP with 1 t ha⁻¹ biochar (BC) applications, all assuming identical wheat yield. The calculations in the model added GST for all biochar purchase price scenarios, while the SSP purchase price included GST. (Bolded numbers and a “-” indicates when the half rate SSP and biochar addition was not cost competitive with the full SSP only rate.)

Figure 1 graphically represents the data in Table 2. The Figure clearly indicates when the full SSP rate application NPC is higher than the range of NPC calculations for the half SSP rate and BC applications over five BC purchase price scenarios (excluding GST). When the NPC of the half SSP rate and BC application are to the bottom right of the full SSP rate NPC calculations for each fertiliser purchase price, applying BC and the half SSP rate is cost effective. The intersection of the lines that represent the half SSP rate with five BC purchase price scenarios and the full SSP rate NPC show the “break-even” point. Each break-even point was calculated for a range of SSP purchase prices which include delivery to farm.

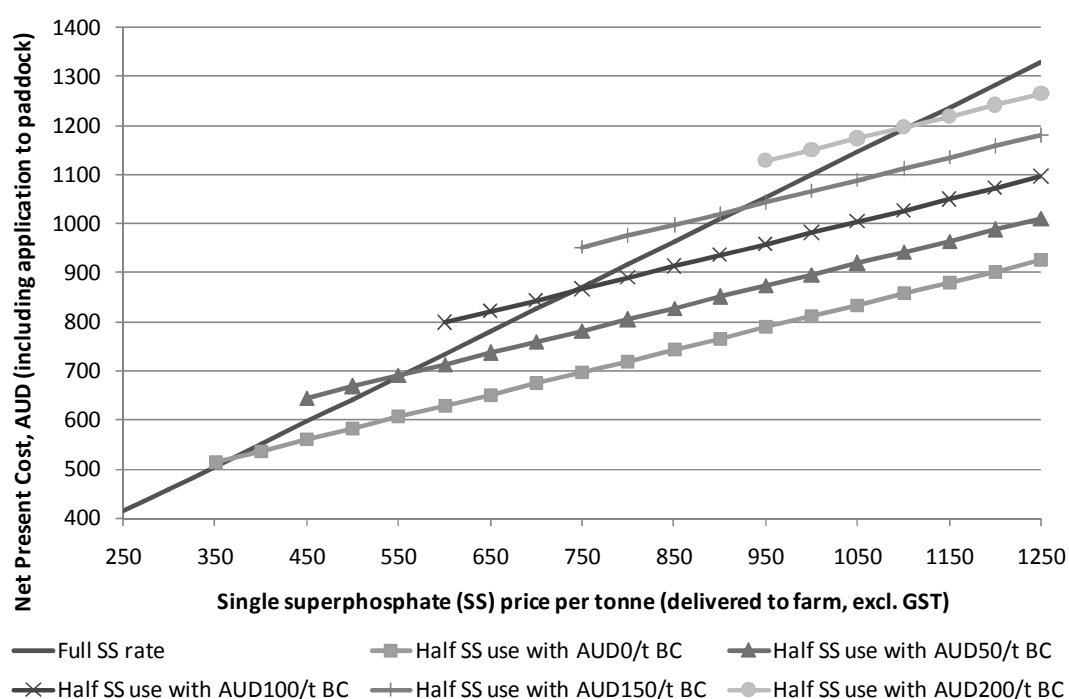


Figure 1: Five NPC calculations of the half SSP rate and BC addition are shown using the scenarios of BC costs (AUD0 to AUD200 t⁻¹). These five NPC scenarios are compared against the NPC of the full SSP rate over a range of SSP prices.

Figure 1 shows that at “current” prices of SSP (generally between AUD200 and AUD450 t⁻¹), the choice of using half SSP application rates with BC additions at the above rates are not an attractive option unless the BC purchase price is zero. Only at very high SSP prices does the half rate option become attractive when the BC purchase prices are less than AUD200 t⁻¹. At the present time BC purchase prices are an order of magnitude higher (>~AUD2,000 t⁻¹) than were modelled in the above scenarios. The above scenarios also do not include an economic value for carbon. Table 4 shows the influence of carbon prices (tCO₂-e⁻¹) on the “net” cost of a range of BC prices. The net cost was calculated assuming the value of carbon in the BC was eligible for a

soil carbon market, and the various potential prices of carbon were subtracted from the gross BC purchase price. Numbers in italics indicate when the carbon value of the stable carbon fraction in the BC price is insufficient to recoup the cost of the BC. Negative numbers indicate when the value of the carbon in the BC is greater than the cost of purchasing BC, and numbers in bold indicate when the value of carbon minus the BC cost is sufficient to cover the additional AUD110 ha⁻¹ BC application cost into the soil.

	Cost of BC (AUD t⁻¹)					
Carbon (AUD tCO₂-e⁻¹)	0	50	100	150	200	250
0	0	50	100	150	200	250
5	-15	35	85	135	185	235
10	-29	21	71	121	171	221
15	-44	6	56	106	156	206
20	-59	-9	41	91	141	191
25	-73	-23	27	77	127	177
30	-88	-38	12	62	112	162
35	-103	-53	-3	47	97	147
40	-117	-67	-17	33	83	133
45	-132	-82	-32	18	68	118
50	-147	-97	-47	3	53	103
55	-161	-111	-61	-11	39	89
60	-176	-126	-76	-26	24	74
65	-191	-141	-91	-41	9	59
70	-205	-155	-105	-55	-5	45
75	-220	-170	-120	-70	-20	30
80	-235	-185	-135	-85	-35	15
85	-249	-199	-149	-99	-49	1
90	-264	-214	-164	-114	-64	-14
95	-279	-229	-179	-129	-79	-29
100	-293	-243	-193	-143	-93	-43

Table 4: The net cost of BC calculated using a range of BC purchase prices (excluding GST), using 3.666 tCO₂-e tC⁻¹, and 80% recalcitrance rates for soil sequestration, multiplied by a range of carbon prices (AUD0-100 tCO₂-e⁻¹).

Table 4 shows that whilst the introduction of a carbon price will effectively subsidise BC costs, very high carbon prices are required for the sequestration value of BC to equal the purchase price, and also cover costs for application to soil. Current very high prices of BC relative to the scenarios above exemplify that the value of carbon will be a small financial benefit to agriculturalists applying BC. Table 5 breaks down the required carbon prices to recoup BC purchase and soil application costs over a larger range of BC costs.

BC cost (AUD t ⁻¹)	50	100	150	200	250	300	350	400
Break-even C price (AUD tCO₂-e)	17	34	51	68	85	102	119	136
BC cost inc. GST (AUD t ⁻¹)	55	110	165	220	275	330	385	440
Break-even C price (AUD tCO₂-e)	19	38	56	75	94	113	131	150
BC + application inc. GST (AUD t ⁻¹)	165	220	275	330	385	400	495	550
Break-even C price (AUD tCO₂-e)	56	75	94	113	131	150	169	188

Table 5: Higher BC prices and the equivalent carbon prices required to recoup the BC purchase price with and without GST, and also including application to soil including GST.

The current low SSP prices, the high market prices for BC, the high BC soil application cost of deep-banding relative to conventional broadcasting, and the current inability of agriculturalists to receive carbon credits from applying BC to soils, renders the halving SSP applications by using BC unattractive. The market adaptation potential of using half SSP applications with 1 t ha⁻¹ of BC in the SW of WA is positive with only very high fertiliser prices and very low BC costs. Table 6 shows an example of the current market adaptation potential calculated using an approximate current SSP price, and a relatively low BC price. The Table also shows the total cost difference and a required carbon price to break-even over the 15 years. The model does not take into account any additional cost or uncertainty of verification sampling regimes for soil BC recalcitrance rates over time, or third-party charges. The Table clearly shows the option of displacing half of the annual SSP fertiliser over the 15 years will cost around twice as much per ha as the full SSP rate option. The carbon price will need to be greater than AUD100 tCO₂-e⁻¹ to recoup the additional expenditure.

NPC of full SSP rate (at AUD350 t ⁻¹ , at 90 kg ha ⁻¹ year ⁻¹)	AUD505
NPC of half SSP rate w/BC (SSP at AUD350 t ⁻¹ , BC at AUD400 t ⁻¹)	AUD1,192
Total difference over the 15 years (AUD ha ⁻¹)	AUD597
Required carbon price to break even (tCO ₂ -e ⁻¹)	AUD102

Table 6: Indicative NPC's between the full SSP rate at roughly current market prices and application costs, and the half SSP rate with the addition of 1 t ha⁻¹ of BC at a relatively low price of AUD400 t⁻¹.)

Comparative Scenario: 1t of BC ha⁻¹ with the Full Rate of SSP

For comparison, an analysis was undertaken of the NPC of applying BC at 1 t ha⁻¹ with the full rate of SSP. Table 1 previously indicated significant yield increases in low rainfall areas of using BC on wheat crops of between 14 and 28% approximately, when used with the half fertiliser rates. This analysis assumes^b that using the full rate of SSP (90 kg ha⁻¹ year⁻¹) with a 1 t ha⁻¹ year⁻¹ application of BC will increase wheat yields by 15% on average over the 15 years relative to full SSP applications only, in the SW of WA. The baseline yield used for the scenario was 1.75 t ha⁻¹, an approximate average wheat yield for WA. This analysis was undertaken to explore the relative impact of using BC to increase yield, as opposed to increasing fertiliser use efficiency.

Table 8 shows the assumptions of the model, including a wheat value increase of AUD71.75 ha⁻¹, based on an increased production of an additional 15% wheat yield from the 1.75 t ha⁻¹, at a value of AUD350 t⁻¹, over the 15 year interval. All values were adjusted for inflation (3% p.a.) and included an 8% discount rate. The scenario did not include any further costs of additional harvesting or transport costs of the additional wheat yield. The model did not require the inclusion of the SSP price, only the BC purchase price and the carbon price. Table 7 summarises the results of a range of carbon values and BC purchase prices. The Table indicates that the required carbon prices to recoup BC purchase price costs are lower when BC is used to increase yield, rather than reduce fertiliser use.

^b This assumption does is not supported by sufficient research at present, although some research suggests it may be possible for certain crops and soil types [8]. For a detailed list of agronomic results see the book "Biochar for environmental management: science and technology", edited by Lehmann et al. (2008), and published by Earthscan.

	Cost of BC (AUD t ⁻¹)					
Carbon (AUD tCO ₂ -e ⁻¹)	200	250	300	350	400	450
0	155	70	-14	-	-	-
5	-	93	8	-77	-	-
10	-	115	31	-54	-	-
15	-	138	53	-31	-	-
20	-	161	76	-9	-	-
25	-	-	98	14	-71	-
30	-	-	121	36	-48	-
35	-	-	144	59	-26	-
40	-	-	166	82	-3	-
45	-	-	-	104	19	-65
50	-	-	-	127	42	-43

Table 7: NPV ha⁻¹ of 1 t ha⁻¹ BC achieving a 15% yield gain over 1.75 t ha⁻¹, with an average wheat price of AUD350 t⁻¹, over the 15 years. (Note the negative NVP scenarios in bold indicate when the BC addition is not cost-effective).

Figure 2 represents the data in Table 7 graphically. The Figure shows that when BC purchase prices are below AUD250 t⁻¹, the application of BC is attractive as a market mitigation option without any carbon price, assuming the additional 15% yield is achieved. The market mitigation potential of the BC application to soil remains at a maximum of 5.866 tCO₂-e ha⁻¹ over the 15 year period. Assuming an AUD400 t⁻¹ purchase price for BC, the market adaptation potential remains negative at AUD184 ha⁻¹. To break even, a carbon price of AUD41 tCO₂-e is required. Whilst this is a relatively high price, it is only 40% of the carbon price required for the scenario with half SSP rate and 1 t ha⁻¹ of BC to be cost effective, when the purchase price of BC is AUD400 t⁻¹ (Table 9). Therefore, the results of this simple scenario suggest that the most cost effective use for BC in terms of a market adaptation potential measures are to simply increase the wheat yield. Whether incorporating BC into fertiliser regimes will be a positive market adaptation measure in practice will be dependent primarily on the purchase price of BC, and to some extent on the price of carbon - if future markets create a commodity of the sequestered carbon in soils.

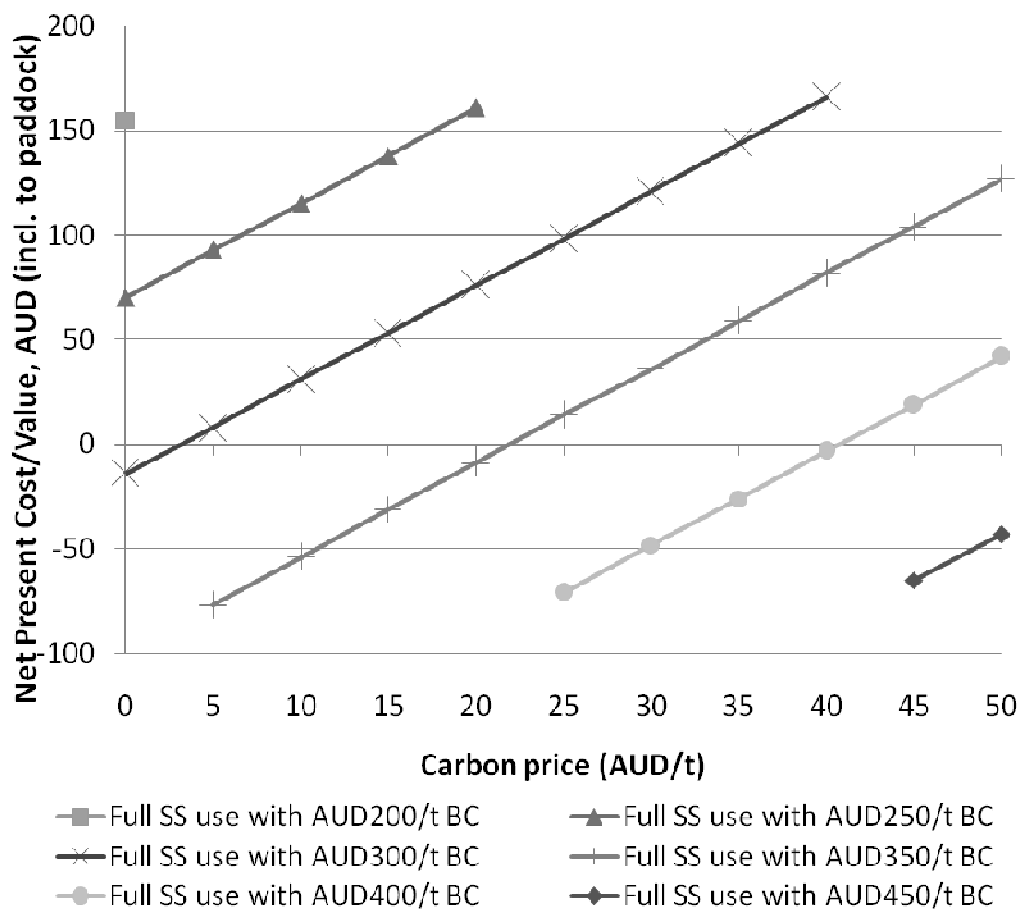


Figure 2: NPV ha^{-1} of 1 t ha^{-1} BC achieving a 15% yield gain over 1.75 t ha^{-1} , with an average wheat price of $\text{AUD}350 \text{ t}^{-1}$, over the 15 years. (Note the negative NVP scenarios indicate when the BC addition is not cost-effective).

NPC of full SSP rate w/BC (BC at $\text{AUD}400 \text{ t}^{-1}$)	AUD184
Required carbon price to break even ($\text{tCO}_2\text{-e}^{-1}$)	AUD41

Table 9: Indicative NPC of the full SSP rate with 1 t ha^{-1} of BC at roughly current market prices and application costs.

Conclusion

This research demonstrated that the use of BC to reduce single superphosphate fertiliser use did not result in cost-effective market adaptation or market mitigation opportunities. In addition, the viability of BC sequestration projects was heavily dependent on a range of variable commodity prices, including carbon, yet primarily on the development of new industrial BC production facilities. This work provides an example where quantification and comparison of a range of options on a “level playing field” can determine both the market adaptation and market mitigation potential of a range of alternative scenarios and the resulting benefits, costs, synergies, and trade-offs. Such information enables farmers, policymakers, and researchers to progress towards the adoption of suitable methods of production that achieve positive benefits for both private entities, and the general public [21]. It is clear that biomass conversion and sequestration projects have the potential to contribute significantly to climate change mitigation, although many options may not be economically attractive at current cost estimates and carbon prices [22]. Therefore, biomass sequestration, biomass conversion, and BC projects may be required to fit into niche applications in a complex blend of production streams at the current time [10]. The results of this research confirm previous assertions that land-based production of biomass for the sole purpose of producing BC may not be economically feasible due to the relatively high BC production costs at present [10]. The production of BC at low costs will likely be achieved in the medium-term as a “waste stream” from a mix of other biomass conversion technologies, such as biofuel production, municipal solid waste processing, or bioenergy (electricity) systems.

Whilst this research provides approximate BC use data, there is a need for additional fundamental research on the impact of BC use in a range of agricultural activities [4]. While noting the lack of exhaustive research supporting many of the assumptions for each BC scenario, the results provide direction for further work that may enable the future implementation of appropriate soil sequestration policies, and fundamental BC research activities such as cost reduction. Increasing scientific certainty of BC use agronomically will reduce risks associated with a potential industrial-scale BC industry and ensure a sustained industrial BC demand enabling lower cost production. With new research, policies and initiatives, the sum profitability of the BC industry may improve, although it is likely to require

integration into existing agricultural production systems. However, as much BC research, technology, and policy is in its infancy or non-existent, much work is needed prior to wide-scale application of BC to soils to provide another option for climate change adaptation and mitigation integration [4].

Finally, the stability of government policy, the opportunity cost of alternative practices, and the administrative burden and investment required for new production systems should be a prime concern. This will require active collaboration between researchers, agriculturalists, scientists, industry, and governments to identify technological and policy options that are the most promising over the long-term [23]. Balancing needs of regional productive industries and ecosystems requires multifunctional agricultural land use incorporating landscapes that can deliver food, employment, security, innovation, all in a sustained manner [24]. Therefore, climate change mitigation researchers and policymakers also need to address private business concerns regarding production security in terms of the contextual technical feasibility, financial viability, and community acceptability of new options [23].

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